Effects of the refractive index of the encapsulant on the light-extraction efficiency of light-emitting diodes

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Abstract: We investigate the effects of the refractive index of the encapsulant on the light-extraction efficiency (LEE) of light-emitting diodes (LEDs) for GaN LEDs ($n \approx 2.5$) and AlGaInP LEDs ($n \approx 3.0$). For non-absorbing rectangular parallelepiped LED chips, as the refractive index of the encapsulant increases, the LEE first increases quasi-linearly, then increases sub-linearly, and finally a saturation is reached. Furthermore, LEDs with a dual-layer graded-refractive-index (GRIN) encapsulant ($n_{encapsulant1}$ = 1.57 and $n_{encapsulant2}$ = 1.41) is fabricated through a two-step curing process. We demonstrate that such an LED further enhances the LEE by reducing Fresnel reflection loss at the encapsulant/air interface by 35% compared with an LED encapsulated with a single-layer encapsulant ($n_{encapsulant}$ = 1.57).

OCIS codes: (230.3670) Light-emitting diodes; (310.4165) Multilayer design.

References and links

1. E. F. Schubert, *Light-Emitting Diodes*, 2nd ed. (Cambridge University Press, 2006).
2. S. Chhajed, W. Lee, J. Cho, E. F. Schubert, and J. K. Kim, "Strong light extraction enhancement in GaInN light-emitting diodes by using self-organized nanoscale patterning of p-type GaN," Appl. Phys. Lett. **98**(7), 071102 (2011).
3. T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, "Increase in the extraction efficiency of GaN-based light-emitting diodes via surface roughening," Appl. Phys. Lett. **84**(6), 855 (2004).
4. J. J. Wierer, Jr., A. David, and M. M. Megens, "III-nitride photonic-crystal light-emitting diodes with high extraction efficiency," Nat. Photonics **3**(3), 163–169 (2009).
5. E. Matioli, E. Rangel, M. Iza, B. Fleury, N. Pfaff, J. Speck, E. Hu, and C. Weisbuch, "High extraction efficiency light-emitting diodes based on embedded air-gap photonic-crystals," Appl. Phys. Lett. **96**(3), 031108 (2010).
6. J. Cho, H. Kim, H. Kim, J. W. Lee, S. Yoon, C. Sone, Y. Park, and E. Yoon, "Simulation and fabrication of highly efficient InGaN-based LEDs with corrugated interface substrate," Phys. Stat. Solidi C **2**(7), 2874–2877 (2005).
7. X. H. Wang, W. Y. Fu, P. T. Lai, and H. W. Choi, "Evaluation of InGaN/GaN light-emitting diodes of circular geometry," Opt. Express **17**(25), 22311–22319 (2009).
8. J. K. Kim, S. Chhajed, M. F. Schubert, E. F. Schubert, A. J. Fischer, M. H. Crawford, J. Cho, H. Kim, and C. Sone, "Light-extraction enhancement of GaInN light-emitting diodes by graded-refractive-index indium tin oxide anti-reflection contact," Adv. Mater. **20**(4), 801–804 (2008).
9. C. H. Chiu, P. Yu, C. H. Chang, C. S. Yang, M. H. Hsu, H. C. Kuo, and M. A. Tsai, "Oblique electron-beam evaporation of distinctive indium-tin-oxide nanorods for enhanced light extraction from InGaN/GaN light emitting diodes," Opt. Express **17**(23), 21250–21256 (2009).
10. F. W. Mont, J. K. Kim, M. F. Schubert, E. F. Schubert, and R. W. Siegel, "High-refractive-index TiO2-nanoparticle-loaded encapsulants for light-emitting diodes," J. Appl. Phys. **103**(8), 083120 (2008).
11. H. Hayashi, J. Takeshita, Y. Uchida, S. Kurai, and T. Taguchi, "Dependence of the light extraction from near-ultraviolet light-emitting diodes on refraction index, transmittance and shape," J. Light Vis. Env. **33**(3), 137–141 (2009).

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12. I. Moreno, D. Bermúdez, and M. Avendaño-Alejo, "Light-emitting diode spherical packages: an equation for the light transmission efficiency," Appl. Opt. **49**(1), 12–20 (2010).
13. Z. Liu, K. Wang, X. Luo, and S. Liu, "Precise optical modeling of blue light-emitting diodes by Monte Carlo ray-tracing," Opt. Express **18**(9), 9398–9412 (2010).

One of the fundamental obstacles facing light-emitting diodes (LEDs) is the occurrence of trapped light inside a high-refractive-index semiconductor [1]. As a result of the total internal reflection (TIR), incident light at a semiconductor/air interface is trapped if the angle of incidence is larger than the critical angle for TIR, θ_C. Thus the light-extraction efficiency (LEE) of LEDs is severely reduced. For example, a planar GaN LED has a LEE as low as 25% [2]. A variety of methods have been reported to increase the LEE of LEDs, including LEDs with textured surfaces [3], LEDs with photonic crystals [4,5], LEDs grown on patterned substrates [6], LEDs with optimized die shapes [7], and LEDs coated with graded-refractive-index anti-reflection coatings [8,9]. Nevertheless, the fundamental obstacle of light extraction still lies in the large refractive-index contrast between the semiconductor and air.

In order to overcome this obstacle, the LED chip is encapsulated in an encapsulant so that both θ_C and the size of the light-escape cone can be increased. So the refractive index of the encapsulant is of great importance to the LEE of LEDs. Thus, we study the effects of the refractive index of the encapsulant on the LEE of GaN LEDs as well as AlGaInP LEDs. The study includes an analytical calculation, a numerical calculation, and a three-dimensional (3D) ray-tracing simulation. Furthermore, LED lamps using different LED chips and encapsulants of different refractive indices are fabricated and measured.

LEDs encapsulated with a multiple-layer graded refractive index (GRIN) encapsulant can further enhance the LEE by reducing Fresnel reflection loss at the encapsulant/air interface [10]. Fresnel reflection loss occurs at the encapsulant/air interface mainly due to the large refractive-index contrast between the encapsulant and air. Other factors, such as the curvature of the encapsulant, the shape of the reflector cup, and the relative position of the LED chip inside the encapsulant, can also affect Fresnel reflection loss by altering the angle of incidence at the encapsulant/air interface [11,12]. One solution to reduce Fresnel reflection loss is to use a multiple-layer GRIN encapsulant, where the refractive index gradually decreases from the first layer which is in contact with the semiconductor, to the last layer which is in contact with air. Compared with the single-layer encapsulant, the multiple-layer GRIN encapsulant can minimize Fresnel reflection loss at the encapsulant/air interface by reducing the refractive-index contrast between the encapsulant and air, thus the LEE of LEDs is further enhanced.

One type of LED chip used in this study has a III–Nitride based active region ($n \approx 2.5$) with a peak emission wavelength of 470 nm and a chip area of 600×200 μm^2 (GaN LEDs). The other type of LED chip has a III–Phosphide based active region ($n \approx 3.0$) with a peak emission wavelength of 615 nm and a chip area of 600×600 μm^2 (AlGaInP LEDs). The LED chips are encapsulated with silicones of three different refractive indices ($n_{\text{encapsulant}} = 1.41$, 1.46 and 1.57) using a 5-mm-round-top molding cup. All silicones are specified by the manufacturer to have a transparency higher than 99% at the thickness of 1 mm for wavelengths ranging from 450 to 800 nm. In addition, unencapsulated LED chips (without any encapsulant) are fabricated and measured. The light output power (LOP) of LEDs is measured by using an integrating sphere. LEDs encapsulated with a multi-layer GRIN encapsulant can further enhance the LEE by reducing Fresnel reflection loss at the encapsulant/air interface. In order to demonstrate this concept, LED lamps encapsulated with a dual-layer GRIN encapsulant ($n_{\text{encapsulant1}} = 1.57$ and $n_{\text{encapsulant2}} = 1.41$) are fabricated and measured. The measured results are compared with those of LEDs encapsulated with a single-layer encapsulant as well as with analytical calculation results.

The LEE of LEDs with encapsulation can be analytically calculated by

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$$\eta_{\mathrm{LEE(encapsulated)}} = \frac{1-\cos\theta_{\mathrm{C,encapsulant}}}{1-\cos\theta_{\mathrm{C,air}}}\eta_{\mathrm{LEE(unencapsulated)}}$$
$$= \frac{1-\cos\left(\arcsin\dfrac{n_{\mathrm{encapsulant}}}{n_{\mathrm{semiconductor}}}\right)}{1-\cos\left(\arcsin\dfrac{1}{n_{\mathrm{semiconductor}}}\right)}\eta_{\mathrm{LEE(unencapsulated)}} \tag{1}$$

where $\eta_{\mathrm{LEE(encapsulated)}}$ and $\eta_{\mathrm{LEE(unencapsulated)}}$ are LEEs of encapsulated and unencapsulated LEDs, respectively; $\theta_{\mathrm{C,encapsulant}}$ and $\theta_{\mathrm{C,air}}$ are critical angles for TIR at the semiconductor/encapsulant and the semiconductor/air interfaces, respectively; and $n_{\mathrm{encapsulant}}$ and $n_{\mathrm{semiconductor}}$ are refractive indices of the encapsulant and the semiconductor, respectively. The LEE calculated from Eq. (1) is shown in Fig. 1. Inspection of the figure reveals that the LEE of an encapsulated LED increases quasi-linearly with $n_{\mathrm{encapsulant}}$ without saturation. However, in Eq. (1) it is assumed that the total escaping light is the sum of the light escaping from each light-escape cone. This does not apply for real LEDs: for example, there are six light-escape cones in a conventional rectangular parallelepiped LED chip, corresponding to its six surfaces. As a result of the expansion of each light-escape cone (as $n_{\mathrm{encapsulant}}$ increases), at a certain point these light-escape cones will overlap with each other. Thus the total escaping light is less than the sum of the light escaping from each light-escape cone. So the quasi-linear relationship between the LEE of LEDs and $n_{\mathrm{encapsulant}}$ will only hold true in the low-refractive-index region, but not in the high-refractive-index region, as shown in Fig. 1.

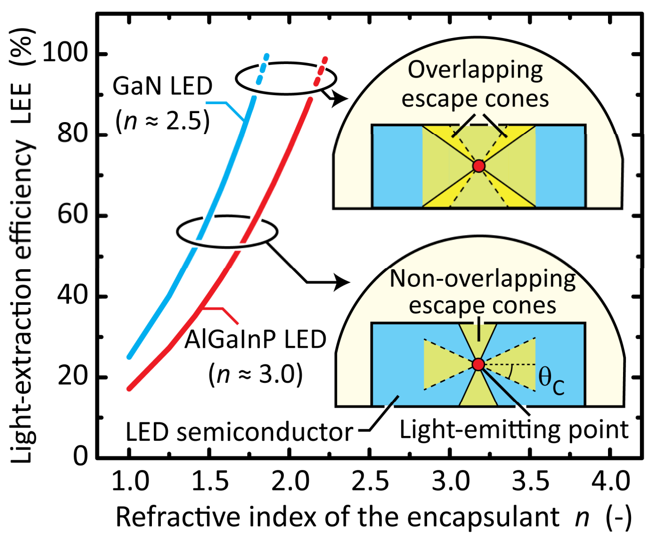

Fig. 1. Analytical calculation of the LEE as a function of the refractive index of the encapsulant for GaN LEDs and AlGaInP LEDs.

A numerical calculation, which takes the overlapping among light-escape cones into account, is performed to calculate the LEE of LEDs. The calculation is based on an isotropic light-emitting source placed at the center of a non-absorbing rectangular parallelepiped LED chip. Using rays emitting into random directions, we determine which rays are inside the light-escape cones and which rays are not. And the LEE is defined as the number of escaping rays over the total number of rays. According to the calculation, for a non-absorbing rectangular parallelepiped LED, when $\theta_C \le 45°$, i.e. when $n_{\mathrm{encapsulant}} \le \left(\sqrt{2}/2\right) n_{\mathrm{semiconductor}}$, there is no overlap among the six light-escape cones. Thus the LEE increases quasi-linearly with θ_C and $n_{\mathrm{encapsulant}}$ as predicted by Eq. (1). However, when $45° < \theta_C < 54.7°$, i.e.

when $\left(\sqrt{2}/2\right)n_{\text{semiconductor}} < n_{\text{encapsulant}} < \left(\sqrt{6}/3\right)n_{\text{semiconductor}}$, the light-escape cones begin to overlap with each other. Thus the LEE increases sub-linearly with θ_C and $n_{\text{encapsulant}}$, since the overlapping among light-escape cones also increases with θ_C. And when $54.7° \le \theta_C < 90°$, i.e. when $\left(\sqrt{6}/3\right)n_{\text{semiconductor}} \le n_{\text{encapsulant}} < n_{\text{semiconductor}}$, the LEE saturates. This is shown in Fig. 2(a).

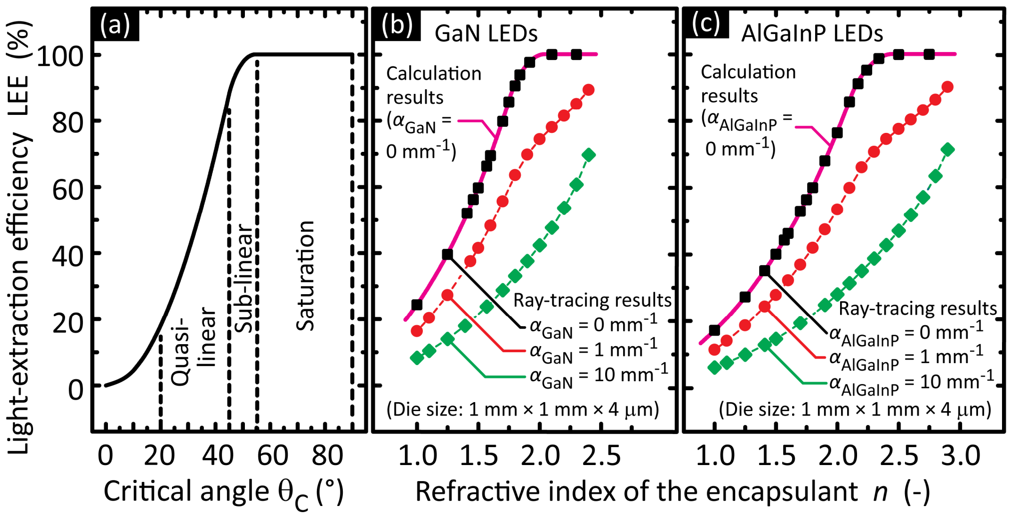

Fig. 2. (a) The numerically calculated LEE as a function of θ_C at the semiconductor/encapsulant interface for a non-absorbing rectangular parallelepiped LED. (b) Numerical calculation results and the 3D ray-tracing simulation results of the LEE as a function of the refractive index of the encapsulant for GaN LEDs. (c) Numerical calculation results and the 3D ray-tracing simulation results of the LEE as a function of the refractive index of the encapsulant for AlGaInP LEDs.

Furthermore, a 3D ray-tracing simulation is performed to obtain the LEE of LEDs. The simulated LED die size is 1 mm × 1 mm and the LED thickness is 4 μm. Fresnel reflection losses are included in all simulations. LEDs with various absorption coefficients are simulated. The 3D ray-tracing simulation results and the numerical calculation results for GaN LEDs and AlGaInP LEDs are shown in Fig. 2(b) and Fig. 2(c), respectively. We find that the 3D ray-tracing simulation results agree very well with the numerical calculation results for both types of non-absorbing LEDs, i.e. as $n_{\text{encapsulant}}$ increases, the LEE first increases quasi-linearly, then increases sub-linearly, and finally a saturation is reached. However, when an LED has a relatively low absorption coefficient ($\alpha = 1$ mm^{-1}), the sub-linear region is extended since the saturation region diminishes due to the absorption. While an LED with a relatively high absorption coefficient ($\alpha = 10$ mm^{-1}) has an LEE that increases super-linearly with $n_{\text{encapsulant}}$ due to the strong absorption of the LED, as shown in Fig. 2(b) and Fig. 2(c).

For encapsulants having a refractive index between 1.4 and 1.6, it is expected that within this range the LEE increases quasi-linearly with $n_{\text{encapsulant}}$ for both GaN LEDs and AlGaInP LEDs. Figure 3 compares the measured LOPs with the 3D ray-tracing simulated LEEs. As shown in Fig. 3, the measured LOP of both types of LEDs increases quasi-linearly with $n_{\text{encapsulant}}$. For GaN LEDs, the LOP of LEDs encapsulated with high-n ($n_{\text{encapsulant}} = 1.57$) encapsulants shows a 5% and 15% enhancement compared with LEDs encapsulated with medium-n ($n_{\text{encapsulant}} = 1.46$) and low-$n$ ($n_{\text{encapsulant}} = 1.41$) encapsulants, respectively. And it shows a 138% enhancement compared with the unencapsulated LEDs. For AlGaInP LEDs, the LOP of LEDs encapsulated with high-n ($n_{\text{encapsulant}} = 1.57$) encapsulants shows a 12% and 15% enhancement compared with LEDs encapsulated with medium-n ($n_{\text{encapsulant}} = 1.46$) and low-$n$ ($n_{\text{encapsulant}} = 1.41$) encapsulants, respectively. And it shows a 90% enhancement

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compared with the unencapsulated LEDs. The 3D ray-tracing simulation results show very similar trends with the measured results when α_{GaN} = 1 mm^{-1} and $\alpha_{AlGaInP}$ = 10 mm^{-1}. These absorption coefficients are reasonable values for both types of materials [13].

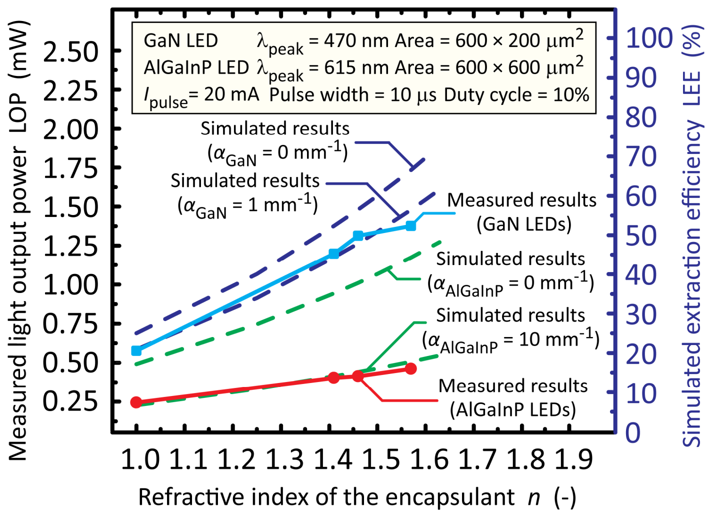

Fig. 3. Comparison between the measured LOP and the 3D ray-tracing simulated LEE as a function of the refractive index of the encapsulant for GaN LEDs and AlGaInP LEDs.

LEDs encapsulated with a multiple-layer GRIN encapsulant can further enhance the LEE by reducing Fresnel reflection loss at the encapsulant/air interface. In order to demonstrate this concept, LED lamps with a dual-layer GRIN encapsulant are fabricated through a two-step curing process. At first, the LED chip is die-bonded to the reflector cup and wire-bonded to the electrodes. After that, a high-*n* silicone is filled into the whole reflector cup so that the LED chip is completely covered. The surface tension of the silicone would result in a dome shape. After that, the LED lamp is heated to cure the high-*n* silicone. And then the lamp is inserted into a molding cup which contains a low-*n* silicone. Finally, the lamp is heated again to cure the low-*n* silicone. The inset of Fig. 4 shows the schematic diagram of such a LED lamp, where $n_{encapsulant1}$ = 1.57 and $n_{encapsulant2}$ = 1.41. The thickness of each layer of the encapsulant is much larger than the wavelength of the emitted light and the interface between two layers is not apparent by visual inspection.

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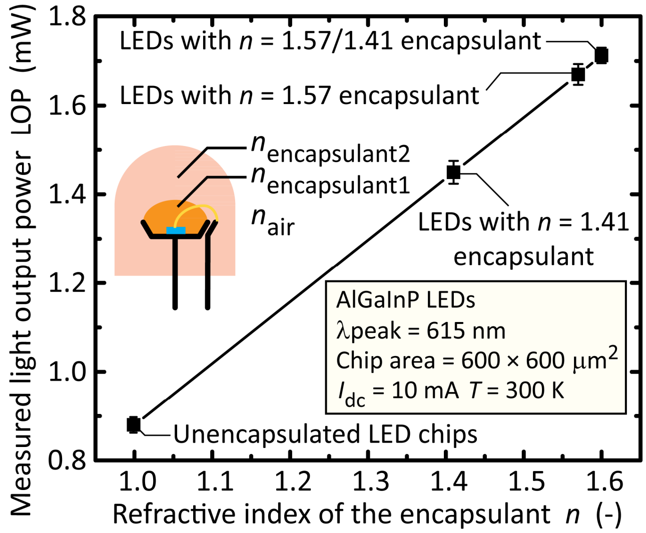

Fig. 4. Measured LOP as a function of the refractive index of the encapsulant for unencapsulated AlGaInP LED chips, AlGaInP LEDs encapsulated with encapsulants having different refractive indices ($n_{\text{encapsulant}}$ = 1.41 and 1.57), and AlGaInP LEDs encapsulated with a dual-layer GRIN encapsulant ($n_{\text{encapsulant1}}$ = 1.57 and $n_{\text{encapsulant2}}$ = 1.41). The inset shows the schematic diagram of a fabricated AlGaInP LED encapsulated with a dual-layer GRIN encapsulant.

Compared with LEDs encapsulated with a single-layer encapsulant ($n_{\text{encapsulant}}$ = 1.57), LEDs encapsulated with a dual-layer GRIN encapsulant ($n_{\text{encapsulant1}}$ = 1.57 and $n_{\text{encapsulant2}}$ = 1.41) have a higher LEE, as shown in Fig. 4. The outer lower-*n* encapsulant can reduce the refractive-index contrast between the inner higher-*n* encapsulant and air, while the inner higher-*n* encapsulant still effectively extracts the light out from the semiconductor. The analytical calculation based on Fresnel's law shows that the reflection at the encapsulant/air interface is decreased by 35% for LEDs encapsulated with a dual-layer GRIN encapsulant ($n_{\text{encapsulant1}}$ = 1.57 and $n_{\text{encapsulant2}}$ = 1.41), corresponding to a LEE enhancement of 2% compared with LEDs encapsulated with a single-layer encapsulant ($n_{\text{encapsulant}}$ = 1.57). The measured results, as shown in Fig. 4, agree with the calculated results. The reduction of Fresnel reflection loss is limited by the small range of refractive indices of encapsulants (currently from 1.4 to 1.6). For example, compared with LEDs encapsulated with a single-layer encapsulant with $n_{\text{encapsulant}}$ = 1.57, the Fresnel reflection loss is expected to be reduced by 49% for LEDs encapsulated with a dual-layer GRIN encapsulant with $n_{\text{encapsulant1}}$ = 1.57 and $n_{\text{encapsulant2}}$ = *1.25*.

In summary, we investigate the effects of the refractive index of the encapsulant on the LEE of GaN LEDs and AlGaInP LEDs. For non-absorbing rectangular parallelepiped LED chips, as $n_{\text{encapsulant}}$ increases, the LEE first increases quasi-linearly, then increases sub-linearly, and finally a saturation is reached. Furthermore, LEDs with a dual-layer GRIN encapsulant ($n_{\text{encapsulant1}}$ = 1.57 and $n_{\text{encapsulant2}}$ = 1.41) are fabricated through a two-step curing process. We demonstrate that such an LED can have a higher LEE by reducing Fresnel reflection loss at the encapsulant/air interface by 35% compared with an LED encapsulated with a single-layer encapsulant ($n_{\text{encapsulant}}$ = 1.57).

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